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CHALLENGES FOR SUCCESSFUL COMMERCIALISATION OF FLY ASH - GGBS GEOPOLYMER BINDER

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ABSTRACT

Traditionally used Ordinary Portland Cement (OPC) is becoming less appealing in the construction field due to some major drawbacks such as depletion of natural resources at a faster pace, high demand for Embodied Energy (EE) during its manufacture and massive Embodied CO_2 emission (ECO_2e) to the environment. In pursuit for an alternative to OPC based concrete, alkaline activated alumino-silicate based inorganic polymer binders, popularly known as geopolymer binders, are being considered as a more sustainable solution. Since 1970's geopolymer binders are used in combination with OPC as partial substitutes but it has not yet gained momentum as a commercially viable alternative to completely substitute OPC for every application. Obstacles in the commercialization of Geopolymer concrete (GPC) are many even though it has several engineering merits and plays a role in recycling industrial waste. In this short communication, we have made every attempt to address these limitations based on our practical experience. We have also made some recommendations to overcome those barriers.

Key words: Alkali activated binder, Cement substitutes, Fly ash, Geopolymer concrete, GGBS

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1. INTRODUCTION

Cement is an inevitable material for construction industry with an annual increase in demand by 5-8% each year globally due to urbanization and economic development [1]. Cement industry alone contributes to almost 8% of the total global CO_2 emission due to the release of CO_2 during calcination of $CaCO_3$ and burning of fossil fuel to provide energy for this reaction. Manufacture of cement also depletes our natural resources like limestone and clay. Efforts are

underway to reduce CO_2 emission from cement industry by using efficient kilns, better fuels, and reducing the proportion of Portland clinker used in cement. During the past several decades novel cement like materials from industrial wastes like fly ash, and slag or minimally processed natural materials like rice husks, and bagasse ash, have been researched and tried as substitutes for cement clinker [2]. However their properties differ from that of Portland cement making them suitable for only niche applications such as precast panels or acid resistant sewer pipes.

Professor Joseph Davidovits, a French scientist, introduced the concept of ‘Geopolymers’ as inorganic alumino-silicate materials from the earth that forms covalently bonded Si-O-Al repeat units or polymers. Using these amorphous materials, he introduced the first geopolymer resin binder in 1979, by treating them with alkaline solutions containing metal ions eg. Sodium silicate [3]. One of the attractions for geopolymer binders is that they harden at room temperature with slow setting, in the presence of Calcium ions [4, 5], giving enough time for mixing them with rock aggregates and carry them to the construction site. Since 1979, researchers around the world have introduced various cementitious materials that can harden when treated with alkali, and practiced using the word ‘geopolymer’ binder/concrete for all alkali-activated binder materials even if they do not form typical Si-O-Al polymers [6, 7]. Please keep in mind that traditionally used Ordinary Portland Cement (OPC) based concrete is also activated with alkali, but they do not fall under the category of ‘Alkali-Activated Binders’. OPC is rich in Calcium content compared to Alkali-activated binders, which are high in Aluminium [8].

Geopolymer binders/concrete are generally stronger and durable than OPC due to the polymerization reaction compared to the hydration reaction in OPC [9], and hence many patents have been granted for this technology [10, 11]. Moreover, lower CO_2 emission and enhanced utilization of industrial waste products makes geopolymer industry an attractive ‘greener’ and viable proposition for replacing OPC. However, it is disappointing to know that popularity of geopolymer or alkali-activated binders never picked up to a commercial level even after four decades since its innovation [6, 12]. One of the biggest drawback of all alkali-activated binder materials is, unlike OPC, their engineering properties are highly variable from place to place due to the differences in chemical composition of raw materials and thus the molecular bonds formed during polymerization reaction. In this paper we have made an attempt to address some of the major obstacles in commercialization of Geopolymer Concrete (GPC) based on our practical experience with fly ash- Ground Granulated Blast-furnace Slag (GGBS) binder for making precast products. We have also made some recommendations to overcome some of these barriers. These are explained in the following categories - 1) Technical difficulties, 2) Inconsistency in the quality and availability of raw materials, 3) Difficulty in making the binder mix, 4) Difficulty in handling fresh geopolymer mortar/concrete, 5) Restricted applicability of geopolymer binders, 6) Issues related to chemical and physical properties of the GPC mix, 7) Statutory issues, 8) Economic viability, 9) Environmental issues and possible health hazards, and 10) Hesitation to accept innovative technology.

2. MATERIALS AND METHODS

Geopolymer paste is commonly prepared by activating Class-F fly ash powder alone or in combination with GGBS powder with an alkaline solution containing Sodium silicate and Sodium hydroxide [13]. We have purchased raw materials from the following vendors: Class-F Fly ash (Mettur Thermal Power Plant, India), GGBS (JSW Cement, India), Sodium silicate (Minar Chemical Industries, India), Sodium hydroxide (Travancore Cochin Chemicals, India). Sodium hydroxide pellets were dissolved in potable water to obtain 8M solution before mixing with Sodium silicate solution. Ratio of Sodium silicate to 8M Sodium hydroxide was 2.5 : 1.0 weight/weight. It is a common practice to add Sodium hydroxide to alkaline activator to achieve

faster setting and higher compressive strength, however due to caustic erosion of precast surfaces and health hazards to construction workers we avoided the use of Sodium hydroxide after our initial trials. Geopolymer paste or concrete with 100% Fly ash require heating at high temperatures (60°C–90°C) for setting and curing [14]. Therefore we have only used Fly ash in combination with GGBS, and were able to successfully carry out setting and curing of the geopolymer paste and concrete at ambient temperature, avoiding the infrastructure needed for heat curing at construction site.

3. OBSTACLES TO COMMERCIALISATION OF FLY ASH – GGBS BINDER

3.1. Technical difficulties

As a general practice, geopolymer paste or concrete mix is activated using a mixture of alkali solution containing Sodium silicate and Sodium hydroxide. However, it should be noted that Sodium hydroxide can cause surface erosion due to the formation of Sodium carbonate, by reacting with atmospheric CO_2. An example from our own experience is shown in Fig. 1A where surfaces of pavement blocks were eroded after three years when alkali solution with Sodium hydroxide was used. We have also shown that by omitting Sodium hydroxide this problem can be resolved (Fig. 1B). It should be noted that addition of Sodium hydroxide is dispensable depending on the type of alumino-silicate mixture used. Presence of GGBS in the binder mix will provide sufficient strength to the concrete without having to use Sodium hydroxide in the activator solution.

Amount of alkali used in GPC technology is much higher than that used in OPC based concrete technology. Hence to prevent corrosive burns on skin due to the causticity of Sodium hydroxide, construction workers have to be educated and trained to use personal protective equipment (PPE) such as gloves, mask, goggles and other protective clothing. Due to these reasons in our experimental trials with Fly ash and GGBS, we have excluded Sodium hydroxide after the few initial trials, instead used 100% Sodium silicate solution as the sole source of alkali.

Yet another technical challenge in compounding geopolymer paste, mortar or concrete mix is to ascertain accurate quantity of water required for the mix without compromising workability and compressive strength. This requires technical skill as it doesn't exactly follow Abram's law (strength is inversely proportional to mass ratio of water to cement) like in the case of OPC based mortar or concrete. While estimating water requirement for GPC even the weight of solids from alkali solution has to be considered. Effective window for water to solids ratio for preparing GPC is narrow (0.25-0.35). Any amount of water lower or higher than optimal would reduce compaction and workability or compressive strength respectively.

Variations in chemical composition of raw materials (explained in detail in the following sections) and their decentralized production from geographically separated industrial plants demands high technical know-how at the construction site for mix designing. Formulating a geopolymer mix with specific design strength for each application requires presence of technically knowledgeable person onsite.

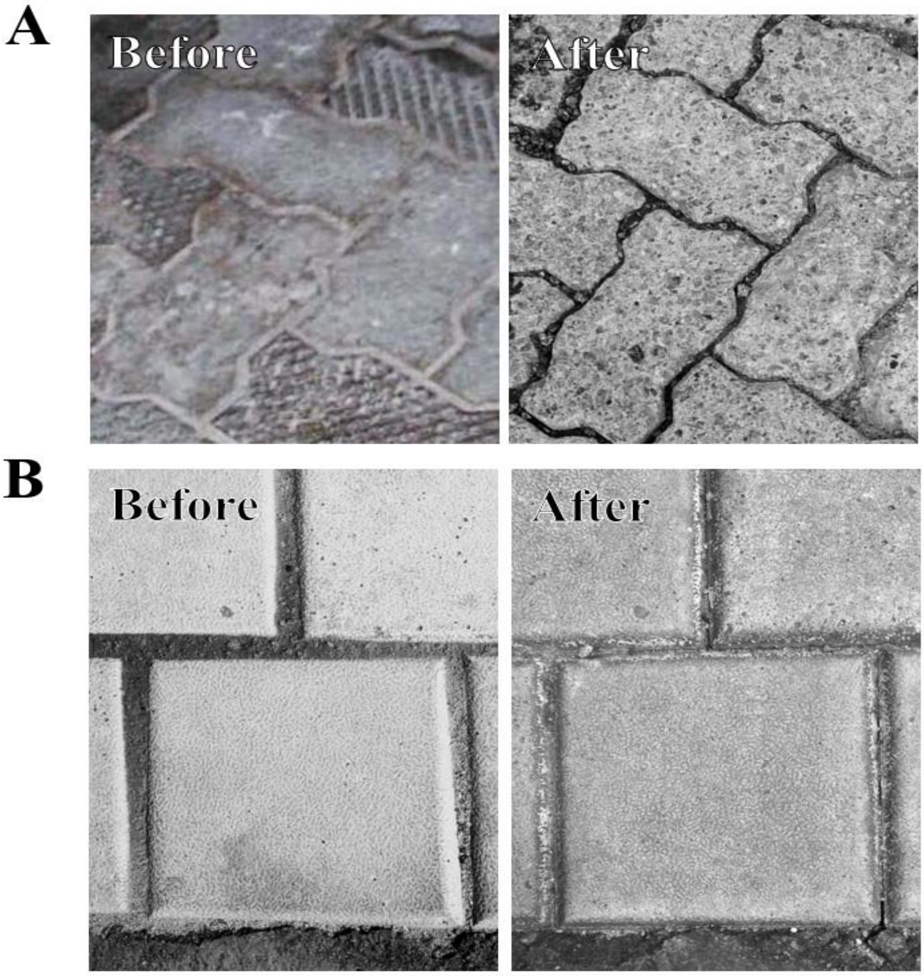

Figure 1 Caustic surface erosion due to Sodium hydroxide in Alkaline activator

F00G100 geopolymer concrete blocks were made (A) with Sodium hydroxide and (B) without Sodium hydroxide in the alkaline activator solution. (A) Potholes in a busy intersection in a city road was filled with geopolymer concrete paver blocks made with Sodium silicate and Sodium hydroxide mixture as alkaline activator. Three years later (right panel) surface of the paver blocks showed signs of erosion/weathering. (B) Ramp from the city road at the front gate of an Engineering institute was paved with geopolymer concrete Tiles made with Sodium silicate alone as alkaline activator. Three years later (right panel) surfaces of the tiles were intact with no signs of surface erosion/weathering.

Suggestion: A possible solution to these difficulties is to (1) pre-analyse chemical composition and optimize ratio of geopolymer binder materials (eg. Fly ash : GGBS) to be used in the absence of Sodium hydroxide, and (2) to provide standardised ready to use geopolymer powder combinations (for each design strength) to customers/users along with clear instructions to use prescribed quantity of Sodium silicate solution per fixed quantity of powder mix. This should simplify complexity of using GPC by non-technical consumers.

3.2. Inconsistency in the Quality and availability of Raw Materials

Geopolymer paste/concrete is made from waste products of various industries and as such their composition and level of impurities cannot be controlled or standardized from one geographical location to the other. Accurate and detailed composition of each of the raw materials i.e. Fly ash, GGBS, and Sodium silicate, has to be pre-analysed before calculating the proportion of each solids and alkaline activator solution. For example, amount of alumina and silica present in the Fly ash material will determine the level of calcium to be provided from GGBS, molarity

of Sodium hydroxide to be used, and the amount of silica to be present Sodium silicate solution. In our experience higher content of unreacted silica slowed down the setting time of GPC and extra water in Sodium silicate solution led to free miscibility. Minor variations in the composition of alumina, silica, calcium, or other ions from impurities, and higher water content in the alkaline activator solution can change the structure of Si-O-Al polymer chain formation. Since compressive strength and durability of GPC is solely dependent on its polymer structure, changes in these micro-environment can detrimentally affect the performance of GPC built products and structures. Therefore simple classification merely based on their CaO, SiO_2, and particle size alone will not provide sufficient information to choose raw materials for GPC.

Though major ingredients for GPC comes from waste products of various industries, they are not generated in sufficiently large quantities to meet the demands of construction industry. Besides, producing large volumes of Sodium silicate solution to meet commercial demands is also difficult.

Suggestions: To a certain extent inconsistency in composition of raw materials can be minimised by pre-analysing and quality testing each material at their source. Care should be taken to maintain identical macro level conditions such as vendor choice, type of alumino-silicate material, weighing equipment, source of potable water, etc. to limit variations introduced onsite. While selecting choices and making decisions, it is preferable to adopt conducive parameters adaptable with site conditions. Throughout our study we sticked to a single source for each of the raw materials to avoid such variability in chemical composition of raw materials. Standardizing an optimum proportion of established ingredients, making ready to use admixtures of those ingredients to meet desired design strength, and using commercially available pre-made Sodium silicate solution can provide consistency in GPC quality and performance.

3.3. Difficulty in Making the Binder Mix

Amount of water used for GPC is comparatively lower (only 0.30 parts of the total solids) than that used for OPC based concrete (0.40-0.50 parts of Portland cement). To achieve efficient polymerization reaction, amount of water to be used in GPC is calculated conservatively based on the total amount of solids in the mix (including that from Sodium silicate solution). Low water content poses difficulty in achieving homogenous mixing of various individual components for geopolymer mix. It also allows a portion of the binder mix to stick to the sides of drum or pan mixer and cause wastage of binder material. Low water to binder ratio also yield stiff geopolymer paste compared to OPC based paste. Preparation of commercial quantities of GPC will be difficult with such low workability especially when more than two ingredients are involved in the making of GPC mix.

Suggestion: For achieving satisfactory mixing, it is advisable to pre-mix powder components (Fly ash, GGBS etc.) by grinding them in a ball mill. Premixed powder can be combined with alkali solution in a flash mixer (Putty mixer) to prepare the paste. The paste slurry can then be poured into drum or pan mixer to mix it with fine and coarse aggregates. This step by step mixing procedure will consistently provide a homogenous intimately mixed GPC.

3.4. Difficulty in handling Fresh Geopolymer Mortar/Concrete

Polymerization reaction of alumino-silicate materials with alkali render them extremely viscous and sticky with a plastic flow [15]. Due to this property geopolymer concrete has fast setting, poor slump retention and is free from segregation of coarse aggregate from mortar matrix. Compacting GPC mixes with such high plastic flow requires heavy vibration. Thus low workability of GPC is an important impediment to commercialization.

Suggestion: To overcome problems due to rheological property of geopolymers, GGBS mix can be complimented with Fly ash (FA) in proportions 70 GGBS: 30 FA to 80 GGBS: 20 FA. Both strength and workability can be achieved even with 0.30 parts water to solids ratio by using GGBS. Stiff rheology obtained by addition of GGBS will be helpful in the production of table vibrated pre-cast products without segregation.

3.5. Restricted applicability of Geopolymer Binders

In addition to the above mentioned rheological property, alkali activated binder materials also possess a greater degree of cohesiveness and adhesiveness to other surfaces. Hence detaching geopolymer mortar from the trowel and plastering of vertical surfaces by dashing the fresh mortar is almost impossible. Application of GPC is less of a problem on horizontal surfaces as flattening can be done satisfactorily with a bull float or Darby.

Suggestion: With the currently available geopolymer technology, their usage is very much application restricted. The major advantage of GPC is its strength. Hence as of now, they are only recommended for precast concrete applications [16] and are also being used for rehabilitation of the interior surfaces of acid sensitive sewage pipes[17, 18]. As of now, Indian government has not recommended GPC for any applications that require reinforced concrete.

3.6. Issues related to Chemical and Physical Properties of the GPC mix

Though geopolymer technology was introduced in the late 1970’s, many parameters and properties of GPC are not yet well characterized. Variability in the chemical composition of raw materials is the main reason. Reports show that flexural modulus (bend modulus) and tensile modulus (Young’s modulus) of some geopolymer concrete mixes are comparable to OPC [19]. Whereas other mechanical properties such as creep behaviour, Poisson’s ratio, permeability, sportively, etc. varied with variations in the type of raw material used [19-22] and are not directly comparable to similar properties of OPC based concrete.

Combinations and proportions of binder materials can be adjusted at user’s choice in order to achieve desired engineering property. For example, addition of CaO rich GGBS can accelerate setting of GPC at ambient temperature and improve compressive strength but with the caveat of higher risk for shrinkage crack [23]. Also, increasing compressive strength without proportionate increase in tensile strength can lead to brittleness of finished products. Therefore design of binder mix has to be carried out judiciously with sufficient background knowledge about the available raw materials and the anticipated outcome from the designed mix.

Suggestions: Reports coming from various studies conducted across the globe are not consistent due to the variations in composition of raw materials. Until ready made mixes are commercially available to the public, trial testing and optimization with locally available powder combinations is the only solution.

3.7. Statutory Issues

Based on the issues and limitations mentioned above, and with the currently available knowledge from research community, a standard code cannot be prescribed for alkali activated binder materials for various applications. Commercialisation of GPC is not practical without approved codes from local government. Bureau of Indian standards has very recently approved a code for precast plain products (Paver tiles, Bricks, man hole cover, concrete cover blocks etc.) using Alkali activated concrete[16].

Suggestions: Long term durability studies using combinations of various alumino-silicate binder materials has to be conducted for local climate conditions (humidity, rain, heat etc.) and geographical locations. Centralized supply of quality controlled raw materials for each nation would be appropriate for getting consistent results. Efforts are being made by researchers across

many laboratories in India to fully characterize GPC technology. But it is a slowly evolving process where only time can tell whether commercialization of GPC will be a success.

3.8. Economic Viability

Bulk of the raw materials in GPC mix is alumino-silicate binder material, which in this particular study, are Fly ash and GGBS. Both of these are industrial waste products and hence inexpensive. Indirect cost incurred for obtaining these two materials to the construction site was their transportation cost. We have purchased both fly ash and GGBS from geographically closer vendors (please see Materials and Methods section) and pre-analysed (cost involved) their chemical composition to determine suitability. Since GGBS is available as bigger particles, grinding it before mixing with Fly ash powder also added indirect cost. Third raw material in geopolymer concrete is the alkali solution. Among the three components, Sodium silicate solution was more expensive than the two alumino-silicate powders in our study. Since the ratio of fine aggregate and coarse aggregate used in GPC is the same as OPC based concrete, the only differences in their cost comparison is the price of raw materials for binder material, alkali solution, transportation cost from various geographical locations to the construction site, quality assurance tests, and grinding of GGBS. When the proportion of GGBS is higher than 70-80 parts, cost of GPC is estimated to be higher than OPC based concrete (unpublished data) but it will be with an added advantage of higher strength compared to OPC based concrete.

Suggestion: Since transportation cost is the major contributor in the economic analysis of Geopolymer concrete, it will be more economical to identify geographically closer sources for each of the raw materials. This is an important point to consider for commercialisation.

3.9. Environmental Issues and Possible Health Hazards

As mentioned in section 3.2, each of the raw materials are tested for only specific chemical components such as CaO or SiO_2 etc. However depending on the industry source, and the raw materials used by them, composition of industrial wastes differ in their impurities and chemical composition[24]. Fly ash contains traces of several heavy metals as impurities. Leaching of heavy metals from fly ash has been reported previously[25, 26], but they are found to be within permissible limit. Another source of possible health hazard is silicates used in GPC industry. They are reported to contain carcinogenic compounds which may contribute to occupational hazards when exposed for longer duration[27]. Currently no reports are available about the health hazards in users of GPC.

Suggestion: When GPC is not efficiently formulated, excess of unreacted raw materials can precipitate. Main reason for leaching from GPC products is due to the increased permeability and presence of unreacted raw materials. By judiciously designing binder mix proportions, and by controlling permeability and surface erosion, we can overcome these environmental issues.

3.10. Hesitation to Accept Innovative Technology

Geopolymer technology is a relatively new field in construction industry with several unknown facts that are yet to be time tested. Like in any other field, resistance to accept any change from traditional OPC based concrete, is due to (a) lack of knowledge about GPC among engineers, contractors, and end users, and (b) lack of confidence due to complexity in design and preparation, and lack of data on long term durability and health hazards.

Suggestion: Time tested results from GPC applications after long term use are essential to convince the potential users who are sceptical about adopting this new technology. To overcome resistance, government should take initiative to adopt GPC technology in public works. Educational sessions and training on geopolymer technology can be conducted at regular intervals to familiarize engineers, contractors and workers.

4. CONCLUSION

Knowing the potential of geopolymer technology, researchers worldwide are working hard to standardize GPC for commercial use. Above list of constraints for commercialization of GPC are not exhaustive and each of those are unique to specific location and application. Once technical staff becomes knowledgeable and skilled in the GPC technology, solving these issues will become less complicated. With special care and attention to design, geopolymers can be made at par with OPC based concrete for several applications. At present, Australia is far ahead of rest of the nations in adopting GPC technology. Taxiway pavement, and turning node for aircraft in Brisbane airport is the largest case of field application with geopolymer technology[28]. There were number of challenges faced during the trials done for this project, however each of those were solved by innovative ideas. If this can be made successful in Australia, researchers are optimistically looking forward to an era where OPC based concrete can be completely replaced by GPC in other countries too, making construction field greener than ever before.

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